

ANTI-GLITCHES WITHIN THE STANDARD SCENARIO OF PULSAR GLITCHES

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Abstract

Recent observation of a sudden spin down, occurring on a timescale not exceeding two weeks, of the magnetar 1E2259+586 (see Archibald et al. 2013, where this event was dubbed an ‘anti-glitch’) has not still received any interpretation in terms of the standard scenario of pulsar glitches proposed by Anderson & Itoh (1975). Motivated by this observation, here we present a toy model that allows, under certain conditions, for anti-glitches in neutron stars within the standard approach.

Subject headings: stars: neutron — stars: magnetars — stars: interiors — stars: rotation

1. INTRODUCTION

The generally accepted scenario of neutron star (NS) glitches, proposed by Anderson & Itoh (1975), assumes that sudden unpinning of a group of vortices from their pinning centers results in an abrupt increase of the observed NS rotation frequency — a glitch. Here we present a toy model which demonstrates that, under certain conditions (in particular, for not too high neutron critical temperature in the outer core, see Sections 4 and 5 for details), an opposite effect — anti-glitch — can take place due to avalanche-like unpinning of vortices. Our model takes into account that superfluid density depends on the relative velocities between the normal and superfluid NS components (hereafter the ΔV -effect; see Section 2). When a group of vortices leaves the superfluid region, the velocity lag between the normal component and pinned superfluid component decreases and, due to the ΔV -effect, the mass of the superfluid fraction increases. Such a redistribution of mass between the normal and superfluid liquid components, which has been ignored so far, can naturally lead to an anti-glitch for certain model parameters. Although there are a number of models describing anti-glitches (see, e.g., Parfrey et al. 2012, 2013; Duncan 2013; Lyutikov 2013; Tong 2014; García & Ranea-Sandoval 2014; Huang & Geng 2014), the proposed effect allows one to explain the ‘sudden’ spin down¹ of the magnetar 1E2259+586 (Archibald et al. 2013) within the generally accepted scenario of NS glitches.

2. SUPERFLUID DENSITY AND THE ΔV -EFFECT

Here we introduce the notion of superfluid density ρ_s and discuss how it can be affected by the relative motion of superfluid and normal currents induced in the system (see below for the definition of superfluid and normal currents). Below we set $\hbar = k_B = 1$.

Let us consider a non-relativistic degenerate Fermi-liquid composed of identical particles. Assume that at a temperature T less than some critical temperature T_c they start to form Cooper pairs (become superfluid). In what follows, we, for simplicity, assume that the particles

pair in the spin-singlet 1S_0 state and ignore the Fermi-liquid effects (in particular, we assume that the particle effective mass coincides with its bare mass m).

Generally, at $T < T_c$ it is instructive to think of the superfluid liquid as consisting of two components, the superfluid and normal ones. The superfluid component, which has a density ρ_s , is associated with the Cooper-pair condensate, while the normal component with the density $\rho_q = \rho - \rho_s$ (ρ is the total liquid density) is associated with the thermal (Bogoliubov) excitations (unpaired particles). A notable property of any superfluid system is that these components can flow, without friction, with two distinct velocities (e.g., Landau et al. 1980; Khalatnikov 2000). As a consequence, the total mass-current density \mathbf{J} (or the momentum density \mathbf{P}) of the liquid can be presented as a sum of two terms,

$$\mathbf{J} = \mathbf{P} = \rho_s \mathbf{V}_s + \rho_q \mathbf{V}_q, \quad (1)$$

where \mathbf{V}_s and \mathbf{V}_q are the velocities of the superfluid and normal components, respectively. Note that the velocity \mathbf{V}_s is related to the momentum $2\mathbf{Q}$ of a Cooper pair by the expression $\mathbf{V}_s = \mathbf{Q}/m$. In the reference frame in which $\mathbf{V}_s = 0$, we have (see, e.g., Landau et al. 1980; Gusakov & Haensel 2005)

$$\mathbf{J}|_{\mathbf{V}_s=0} = \mathbf{P}|_{\mathbf{V}_s=0} = \sum_{\mathbf{p}, \sigma} \mathbf{p} f(E_{\mathbf{p}} + \mathbf{p} \Delta \mathbf{V}), \quad (2)$$

where the summation goes over the Fermi momenta \mathbf{p} and spin states σ of the Bogoliubov thermal excitations; $\Delta \mathbf{V} \equiv \mathbf{V}_s - \mathbf{V}_q$; $f(x) = 1/(e^{x/T} + 1)$ is the Fermi-Dirac distribution function for thermal excitations; $E_{\mathbf{p}} = \sqrt{v_F^2(|\mathbf{p}| - p_F)^2 + \Delta^2}$ is their energy in the reference frame in which $\mathbf{V}_s = 0$; p_F and $v_F = p_F/m$ are the particle’s Fermi momentum and Fermi velocity, respectively.

Finally, Δ is the superfluid energy gap, which generally depends on both T and $|\Delta \mathbf{V}| \equiv \Delta V$: $\Delta = \Delta(T, \Delta V)$. The fact that sufficiently large ΔV can affect the gap was emphasized by Bardeen (1962) (see also Gusakov & Kantor 2013; Glampedakis & Jones 2014, where this effect was discussed in application to NSs). In the absence of currents ($\Delta \mathbf{V} = 0$) gap can be approx-

¹ The actual spin down timescale is not known but does not exceed two weeks. Archibald et al. (2013) dubbed this phenomenon an ‘anti-glitch’.

imated as (Yakovlev et al. 1999)

$$\Delta(T, 0) = T \sqrt{1 - \tau} (1.456 - 0.157/\sqrt{\tau} + 1.764/\tau) \quad (3)$$

($\tau \equiv T/T_c$) and decreases from the value $\Delta_0 = 1.764 T_c$ at $T = 0$ to 0 at $T = T_c$. The dependence of Δ on ΔV at $T = 0$ is similar: it decreases from Δ_0 at $\Delta V = 0$ to 0 at $\Delta V \equiv \Delta V_0 = e\Delta_0/(2p_F)$ (see Gusakov & Kantor 2013 for details). In an arbitrary frame equation (2) can be rewritten as

$$\mathbf{J} = \mathbf{P} = \rho \mathbf{V}_s + \sum_{\mathbf{p}, \sigma} \mathbf{p} f(E_{\mathbf{p}} + \mathbf{p} \Delta \mathbf{V}). \quad (4)$$

Equations (1) and (4) allow us to find expression for the normal density ρ_q and hence for the superfluid density $\rho_s = \rho - \rho_q$,

$$\rho_q = - \sum_{\mathbf{p}, \sigma} \frac{\mathbf{p} \Delta \mathbf{V}}{\Delta V^2} f(E_{\mathbf{p}} + \mathbf{p} \Delta \mathbf{V}). \quad (5)$$

As follows from this formula, ρ_q and ρ_s not only depend on T but also on ΔV (this is the ΔV -effect announced in the beginning of the section); the latter dependence is especially pronounced at $p_F \Delta V \sim \Delta(T, 0)$. Usually, however, one considers a situation in which $p_F \Delta V \ll \Delta(T, 0)$. Then two simplifications can be made. First, one can neglect the dependence of the gap on ΔV , $\Delta(T, \Delta V) \approx \Delta(T, 0)$ (Gusakov & Kantor 2013). Second, one can expand the function $f(E_{\mathbf{p}} + \mathbf{p} \Delta \mathbf{V})$ in equation (5) in Taylor series, retaining only the term linear in $\Delta \mathbf{V}$. The resulting expression for ρ_q reduces then to the standard one (e.g., Landau et al. 1980) and is independent of ΔV ,

$$\rho_q = - \sum_{\mathbf{p}, \sigma} \frac{(\mathbf{p} \Delta \mathbf{V})^2}{\Delta V^2} \frac{df(E_{\mathbf{p}})}{dE_{\mathbf{p}}}. \quad (6)$$

As it will be clear from the subsequent consideration, the condition $p_F \Delta V \ll \Delta$ is not necessarily satisfied in NSs. Hence in what follows we will make use of the more general formula (5) rather than the standard equation (6).

Figure 1 illustrates the dependence of $\rho_s = \rho - \rho_q$ on ΔV for seven stellar temperatures: $T/T_c = 0, 0.2, 0.4, 0.6, 0.75, 0.85$, and 0.95 . At $T/T_c \ll 1$, when ΔV is small, all particles are paired and $\rho_s \approx \rho$. As the velocity lag ΔV becomes larger, the superfluid fraction decreases and eventually disappears ($\rho_s = 0$) at $\Delta V = \Delta V_0 = e\Delta_0/(2p_F)$.

3. HOW DOES THE ΔV -EFFECT TURN A GLITCH INTO AN ANTI-GLITCH?

The standard glitch scenario teaches us that when the crust slows down, pinned superfluid stays rotating with a higher frequency Ω_s , because vortices, which determine Ω_s , cannot freely escape from the pinning region. (Note that by the ‘crust’ we understand not only the solid crust itself but also all the NS components rigidly coupled to it. They include non-superfluid and charged particles, neutron thermal Bogoliubov excitations, as well as unpinned superfluid neutron component.) At some moment a group of vortices unpins (the actual unpinning mechanism is unknown but is not important for us here) and transfers angular momentum to the crust. In the standard scenario this event leads to decrease of Ω_s and, due

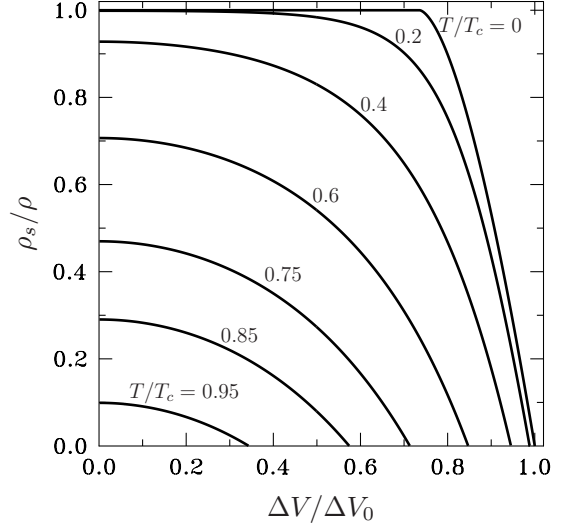


FIG. 1.— Superfluid density ρ_s in units of the total density ρ as a function of the velocity lag ΔV normalized to ΔV_0 for seven stellar temperatures.

to angular momentum conservation, to increase of Ω_c . However, the standard consideration ignores the ΔV -effect. How will Ω_c change if we account for it? The answer follows from the angular momentum conservation,

$$I_{c0}\Omega_{c0} + I_{s0}\Omega_{s0} = I_{c1}\Omega_{c1} + I_{s1}\Omega_{s1}, \quad (7)$$

where the subscripts 0 and 1 refer to the corresponding quantities before and after the glitch, respectively. In equation (7) I_s is the moment of inertia of the pinned superfluid component; $I_c = I - I_s$ is the moment of inertia of the remaining components; I is the total stellar moment of inertia. In the non-relativistic limit I_s is given by the integral over the pinning region,

$$I_s = \int_{\text{pinning region}} \rho_s(T, \Delta\Omega r \sin\theta) r^2 \sin^2\theta dV, \quad (8)$$

and depends on the rotation lag $\Delta\Omega$. Here ρ_s is the neutron superfluid density; r is the radial coordinate, θ is the polar angle, and dV is the volume element.

Taking into account that the variation $\delta\Delta\Omega \equiv \Delta\Omega_1 - \Delta\Omega_0 = (\Omega_{s1} - \Omega_{c1}) - (\Omega_{s0} - \Omega_{c0})$ of the rotations lag in the glitch event is much smaller than $\Delta\Omega_0$, one can expand $I_s(\Delta\Omega)$ and $I_c(\Delta\Omega)$ in Taylor series near the point $\Delta\Omega = \Delta\Omega_0 = \Omega_{s0} - \Omega_{c0}$ and rewrite equation (7) in the form

$$\begin{aligned} I_{c0}\Omega_{c0} + I_{s0}\Omega_{s0} = & [I_{c0} + I'_c(\delta\Omega_s - \delta\Omega_c)](\Omega_{c0} + \delta\Omega_c) + \\ & [I_{s0} + I'_s(\delta\Omega_s - \delta\Omega_c)](\Omega_{s0} + \delta\Omega_s), \end{aligned} \quad (9)$$

where $I'_c = -I'_s = dI_c/d(\Delta\Omega)$; $\delta\Omega_s = \Omega_{s1} - \Omega_{s0}$ and $\delta\Omega_c = \Omega_{c1} - \Omega_{c0}$. Equation (9) yields

$$\delta\Omega_c = - \frac{I_{s0} - I'_c\Delta\Omega_0}{I_{c0} + I'_c\Delta\Omega_0} \delta\Omega_s. \quad (10)$$

This formula reduces to the standard result, $\delta\Omega_c = -I_{s0}/I_{c0} \delta\Omega_s$, if one sets $I'_c = 0$. Because $I'_c = -I'_s > 0$ (superfluid density ρ_s decreases with increasing $\Delta\Omega$), $\Delta\Omega_0 = \Omega_{s0} - \Omega_{c0} > 0$, and $\delta\Omega_s = \Omega_{s1} - \Omega_{s0} < 0$, it follows from equation (10) that we shall observe an abrupt

pulsar spin down (an anti-glitch; $\delta\Omega_c < 0$) if $I'_c\Delta\Omega_0 > I_{s0}$ or, equivalently,

$$|I'_s|\Delta\Omega_0 > I_{s0}. \quad (11)$$

Thus, when anti-glitch occurs both the pinned superfluid and the rest of the star decelerate ($\delta\Omega_c, \delta\Omega_s < 0$), while the moment of inertia redistributes (via formation of additional Cooper pairs) to satisfy the angular momentum conservation.

4. PHYSICS INPUT

As follows from equation (11), for anti-glitch to occur it is necessary to have a relatively large $|I'_s|$. In other words, the superfluid neutron density $\rho_s(T, \Delta\Omega r \sin\theta)$ in the pinning region should be quite sensitive to a variation of $\Delta\Omega$ [see equation (8)]. As discussed in Section 2, for that it is necessary to have $p_F \Delta V \sim \Delta(T, 0)$ or $p_F \Delta\Omega r \sin\theta \sim \Delta(T, 0)$ [here and below the quantities p_F , $\Delta(T, 0)$, ΔV , T_c etc. refer to neutrons]. From this estimate one obtains a typical value $\Delta\Omega_{\text{typ}}$ of the rotation lag $\Delta\Omega$, at which one can expect to have an anti-glitch,

$$\Delta\Omega_{\text{typ}} \sim 1 \left[\frac{\Delta(T, 0)}{10^8 \text{ K}} \right] \left(\frac{n_0}{n} \right)^{1/3} \left(\frac{10^6 \text{ cm}}{r} \right) \text{ rad s}^{-1}, \quad (12)$$

where $n_0 = 0.16 \text{ fm}^{-3}$ is the nucleon number density in atomic nuclei; $n = p_F^3/(3\pi^2)$ is the neutron number density. Generally, $\Delta\Omega_{\text{typ}}$ increases with T_c (see equation 3).

The condition (12) can hardly be satisfied in the crust, because T_c there is larger than 10^9 K everywhere except for the narrow regions at the slopes of the neutron critical temperature profile $T_c(\rho)$. The corresponding values of $\Delta\Omega_{\text{typ}}$ are much higher than possible frequency lags sustained by the vortex pinning (see Link 2014; Seveso et al. 2014). But this condition is very likely to be met in the core.

Recently Chamel (2012) has demonstrated that entrainment in the crust can be strong. If correct, this result indicates that the crust is probably not enough to explain pulsar glitches so that the core superfluid may be responsible for glitches as well (Andersson et al. 2012; Chamel 2013; see, however, Steiner et al. 2014; Piekarewicz et al. 2014). It is generally accepted (e.g., Baym et al. 1969) that protons in the core form type II superconductor which harbors magnetic field confined to flux tubes (for a discussion of other possibilities see Link 2003; Jones 2006; Charbonneau & Zhitnitsky 2007; Alford & Good 2008 and references therein). Neutron vortices pin to magnetic flux tubes in the same way as they pin to nuclei in the crust. Purely poloidal configuration of the magnetic field cannot immobilize vortices so that they freely escape from the core as NS slows down. On the opposite, toroidal component efficiently prevents vortices from moving outwards (Sidery & Alpar 2009; Gügercinoğlu & Alpar 2014). A number of numerical simulations in non-superfluid NSs (Braithwaite 2009; Ciolfi & Rezzolla 2013) and in superconducting NSs (Lander et al. 2012; Lander 2013, 2014) show that toroidal component of the magnetic field, localized in outer layers of the NS core, is necessary for stability of the magnetic field configuration. These simulations demonstrate that toroidal field, which can be noticeably higher than the surface magnetic field, is confined

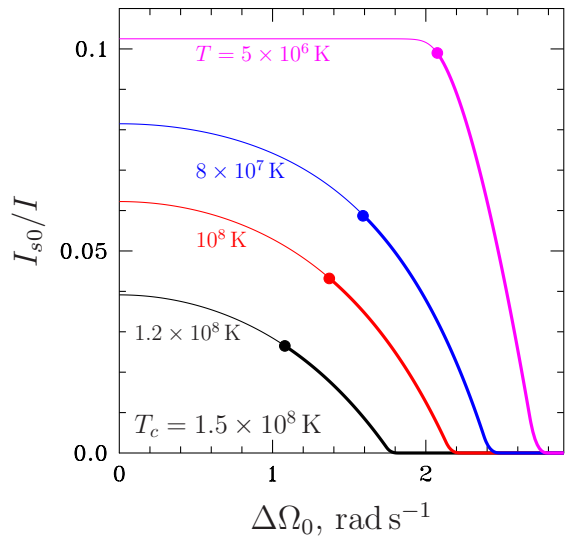


FIG. 2.— Moment of inertia of the pinned superfluid I_{s0} (in units of I) versus rotation lag, $\Delta\Omega_0$, for four values of the stellar temperature. For each temperature filled circle indicates a minimum value of $\Delta\Omega_0$ required to transform a glitch to an anti-glitch. At smaller $\Delta\Omega_0$ (thin lines) we observe glitches, at higher $\Delta\Omega_0$ (thick lines) — anti-glitches.

within the equatorial belt of the width $\sim 0.1R$ (R is the stellar radius) at a distance $r \sim 0.8R$ from the center (Lander et al. 2012; Lander 2013, 2014; Ciolfi & Rezzolla 2013). For definiteness, in our numerical calculations we assume that the pinning region, which coincides with the localization region of the toroidal field, has the form of a torus with coordinates $r \in [0.75R, 0.85R]$, $\theta \in [\pi/2 - \pi/12, \pi/2 + \pi/12]$, $\phi \in [0, 2\pi]$, where ϕ is the azimuthal angle. The moment of inertia pinned to such a region is about $I_s \sim 0.1I$ for $\Delta V = 0$ and $T = 0$ (see Figure 2 and a similar estimate of Gügercinoğlu & Alpar 2014).

The rotation lag $\Delta\Omega_0$, at which glitch/anti-glitch occurs, is uncertain. Clearly, it cannot exceed the maximum value of the critical lag $\Delta\Omega_{\text{cr}}$ in the pinning region, required to unpin vortices from flux tubes by the Magnus force. A typical energy of vortex pinning to flux tubes is of the order of 100 MeV [see Link 2014 and formula (A13) of Ruderman et al. 1998]. It corresponds to $\Delta\Omega_{\text{cr}} \sim 0.1B_{12}^{1/2} \text{ rad s}^{-1}$ (a more refined estimate can be found in Link 2014). In case of magnetars we obtain $\Delta\Omega_{\text{cr}} \sim (1 - 3) \text{ rad s}^{-1}$ for the magnetic field in the core $B \sim 10^{14} - 10^{15} \text{ G}$. Below $\Delta\Omega_0$ will be treated as a free parameter of our toy model.

The value of T_c in the core is also uncertain and varies from 10^7 K (Schwenk & Friman 2004) to $10^9 - 10^{10} \text{ K}$ (e.g., Baldo et al. 1998). Note that, to calculate the gap the latter authors used bare neutron-neutron interactions and ignored medium polarization effects, which can substantially overestimate T_c (Gezerlis et al. 2014). For illustration, in our calculations we choose $T_c = 1.5 \times 10^8 \text{ K}$ in the pinning region (T_c in the inner core can be larger). This value does not contradict the results of microscopic calculations and, e.g., is close to T_c reported by Dong et al. (2013). It also agrees with the predictions of minimal cooling scenario (see, e.g., model a2 in figure 12 of Page et al. 2013).

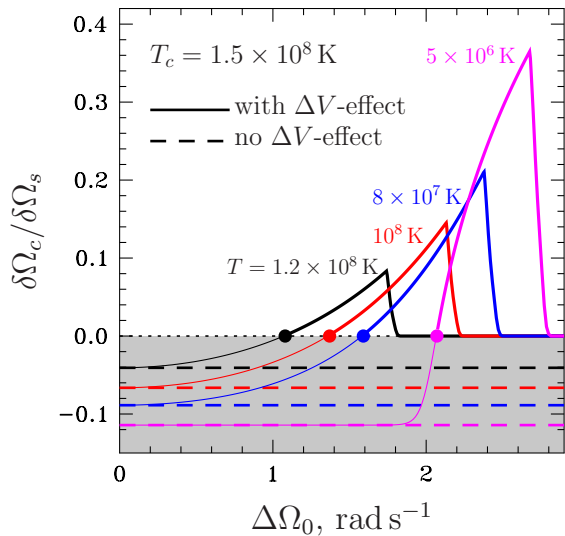


FIG. 3.— Relative variation of the observed rotation frequency versus initial rotation lag $\Delta\Omega_0$. Dashed lines are calculated ignoring the ΔV -effect. An anti-glitch corresponds to $\delta\Omega_c/\delta\Omega_s > 0$ (unshaded region). Other notations are the same as in Figure 2.

5. RESULTS

Using input parameters from Section 4, we analyzed whether anti-glitches are possible if we allow for the ΔV -effect. Our results are shown in Figures 2 and 3. To plot the figures we employed APR equation of state (Akmal et al. 1998) and considered a NS with the mass $M = 1.4M_\odot$.

Figure 2 presents the normalized moment of inertia of the pinned superfluid I_{s0} , calculated with equation (8), as a function of the rotation lag, $\Delta\Omega_0$. The function $I_{s0}(\Delta\Omega_0)$ is plotted for four typical (Kaminker et al. 2014; Viganò et al. 2013) values of magnetar temperature, $T = 1.2 \times 10^8$ K (black lines online), $T = 10^8$ K (red lines online), $T = 8 \times 10^7$ K (blue lines online), and $T = 5 \times 10^6$ K (magenta lines online). At small rotation lags $|I'_s|$ is too small to meet the condition (11) (see thin lines in the figure), but it increases with $\Delta\Omega_0$. Then, at some value of $\Delta\Omega_0$ (marked with filled circles) $|I'_s|\Delta\Omega_0$ and I_{s0} become equal to one another and at higher $\Delta\Omega_0$ the inequality (11) is always hold (then a vortex avalanche leads to an anti-glitch; thick lines in the figure).

Figure 3 presents the ratio $\delta\Omega_c/\delta\Omega_s$ [see equation (10)] versus $\Delta\Omega_0$. We remind the reader that $\delta\Omega_c$ is the observed rotation frequency jump, while $\delta\Omega_s$ is the frequency jump of the pinned superfluid component. In the standard glitch scenario $\delta\Omega_s$ is negative and depends on the number of unpinned vortices and on the place in the star where they repin. It is thus a poorly constrained parameter.

The curves are plotted for the same set of temperatures as in Figure 2. When $\Delta\Omega_0$ is small the ΔV -effect is negligible and solid lines almost coincide with the corresponding dashed lines, which are calculated ignoring this effect. As $\Delta\Omega_0$ increases, $\delta\Omega_c/\delta\Omega_s$ also increases and eventually reaches 0 (this moment is shown by filled circles in the figure). At larger rotation lags $\delta\Omega_c$ becomes negative ($\delta\Omega_c/\delta\Omega_s$ is positive); then vortex avalanche leads to an

anti-glitch, which generally has a similar size $|\delta\Omega_c|$ as glitches at the same $\delta\Omega_s$. Note that, for higher temperatures $\Delta(T, 0)$ is smaller and a lower rotation lag is required to produce an anti-glitch [see estimate (12)].

Further increase of $\Delta\Omega_0$ leads to a gradual shrinking of the pinning region (due to transformation of the superfluid matter to normal matter with growing $\Delta\Omega_0$). This leads to a rapid decrease of $|I'_s|$ (see Figure 2) and hence to a sharp decrease of $\delta\Omega_c/\delta\Omega_s$. Finally, when the superfluidity is completely destroyed in the whole pinning region, neither glitches nor anti-glitches are possible ($\delta\Omega_c/\delta\Omega_s = 0$).

As follows from Figure 3, anti-glitches can be produced for $\Delta\Omega_0 \gtrsim (1-2) \text{ rad s}^{-1}$, in agreement with the estimate (12). Such values of $\Delta\Omega_0$ are comparable to the critical rotation lag $\Delta\Omega_{\text{cr}}$, estimated in Section 4 (recall that $\Delta\Omega_0$ cannot exceed $\Delta\Omega_{\text{cr}}$). Thus, the standard glitch scenario can account for anti-glitches. Note, however, that this conclusion is sensitive to the assumed value of T_c in the pinning region. For example, for $T_c \sim 10^9$ K (e.g., Baldo et al. 1998) one has $\Delta\Omega_0 \sim \Delta\Omega_{\text{typ}} \sim 10 \text{ rad s}^{-1}$; for such T_c anti-glitches will hardly occur in our model unless $\Delta\Omega_{\text{cr}}$ is substantially larger for some reason.

6. DISCUSSION AND CONCLUSION

Here we propose a toy model that allows us to describe an anti-glitch within the standard scenario of pulsar glitches formulated by Anderson & Itoh (1975). The main feature of our model is account for the so-called ΔV -effect — the dependence of the superfluid density on the relative velocity of normal and superfluid components (see Section 2).

We predict that magnetars are the most promising anti-glitching objects. High magnetic field of magnetars provides strong pinning of vortices to flux tubes in the outer core, which leads to a large rotation lag between the normal and superfluid components. As we showed, such a rotation lag may be sufficient to transform a glitch to an anti-glitch.

Could similar mechanism produce anti-glitches in the crust of a magnetar or an ordinary pulsar? Most probably not, because the critical rotation lag $\Delta\Omega_{\text{cr}}$ (see Section 4) seems to be noticeably smaller (Link 2014; Seveso et al. 2014) than the typical rotation lag $\Delta\Omega_{\text{typ}}$ [see equation (12)], which is needed to affect ρ_s . There are two reasons for that. First, the pinning force per unit length is weaker for pinning to crust nuclei than for pinning to flux tubes in the core of a magnetar. Second, the rotation lag ($\sim \Delta\Omega_{\text{typ}}$), that can lead to an anti-glitch in the crust, is severalfold larger than in the core, because the neutron critical temperature T_c in the crust is higher. Due to these two factors it seems implausible that vortex avalanches in the crust can lead to a substantial redistribution of the stellar moment of inertia and thus to an anti-glitch. However, if, due to some reason, vortex unpinning occurs exclusively in the narrow region where T_c is substantially lower (i.e., on the slopes of the critical temperature profile), then anti-glitches could, in principle, be produced.

We summarize by concluding that: (i) the same magnetar can exhibit both glitches (due to vortex unpinning in the crust) and, under certain conditions, anti-glitches (due to vortex unpinning in the core) and (ii) it is not very likely that ordinary pulsars can demonstrate any

anti-glitching activity.

This is an extended version of the contribution presented at the conference “Physics of neutron stars — 2014” (July 28 – August 1, 2014, St.-Petersburg, Russia).

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